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## The Non-thermal Radio Jet Toward the NGC 2264 Star Formation Region

Alfonso Trejo and Luis F. Rodríguez

*Centro de Radioastronomía y Astrofísica, UNAM, Apdo. Postal 3-72, Morelia, Michoacán, 58089 México*

### ABSTRACT

We report sensitive VLA 3.6 cm radio observations toward the head of the Cone nebula in NGC 2264, made in 2006. The purpose of these observations was to study a non-thermal radio jet recently discovered, that appears to emanate from the head of the Cone nebula. The jet is highly polarized, with well-defined knots, and one-sided. The comparison of our images with 1995 archive data indicates no evidence of proper motions nor polarization changes. We find reliable flux density variations in only one knot, which we tentatively identify as the core of a quasar or radio galaxy. An extragalactic location seems to be the best explanation for this jet.

*Subject headings:* radio continuum: galaxies — jets: non-thermal emission

### 1. Introduction

Reipurth et al. (2004) searched for radio continuum emission from proto-stellar objects in eight regions of star formation. In the NGC 2264 region they discovered a remarkably collimated radio jet, less than one arcminute away from the head of the well-known Cone Nebula and apparently emanating from it (see Fig. 1). Furthermore, the total flux density of the jet at 3.6 cm is  $\sim 11$  mJy and the *a priori* probability of finding a background source with this flux density in a region of  $2' \times 2'$  is only 0.0004 (Windhorst et al. 1993), suggesting a possible association between the jet and the Cone Nebula.

The Cone nebula, discovered in 1784 by William Herschel, is believed to be a pillar of gas and dust whose head is most probably externally ionized by S Mon, a massive O-type binary (Gies et al. 1997) located about  $30'$  to the north of the nebula. The head of

the Cone Nebula is a dense ( $\sim 10^4 \text{ cm}^{-3}$ ) molecular core with an estimated mass of  $16 M_{\odot}$  (Pagani & Nguyen-Q-Rieu 1987). The position where the jet is located has one of the highest surface densities of T Tau stars in the region (Dahm & Simon 2005). These circumstances suggested that the radio jet could be physically associated with a young stellar object of the region. Spectacular optical jets emanating from the head of dust pillars have been found in the Trifid (e. g. Yusef-Zadeh, Biretta, & Wardle 2005) and in Carina (<http://antwrp.gsfc.nasa.gov/apod/ap070430.html>).

The overall extent of the jet is about  $28''$ , and (with subarcsec resolution) it seems to be composed by eight knots. Reipurth et al. (2004) found that assuming that the jet was in the NGC 2264 region (at a distance of 760 pc; Sung et al. 1997) and that the knots were moving with a velocity of  $100 \text{ km s}^{-1}$  in the plane of the sky, an ejection every 60 years was implied. This timescale is consistent with that found for knots in jets associated with young stellar objects (e. g. Curiel et al. 1993).

On the other hand, due to the non-thermal nature of its emission and that the jet also presents a high degree of polarization, Reipurth et al. (2004) concluded that these characteristics were consistent with an extragalactic jet. The authors found no obvious counterparts in the IRAS catalogs or at  $2.2 \mu\text{m}$  emission, nor with the *HST* observations. A search in the SIMBAD database shows only two stars; V367 Mon and NGC 2264 LBM 6255 (Lamm et al. 2005) in the region of the jet, but neither clearly associated with any of the knots (see Fig. 1).

In this work we report an analysis of this jet, using both new as well as archive VLA radio data. Our main goal was to compare images taken at two different epochs to search for proper motions and variability that could allow us to favor a galactic or an extragalactic nature for the jet. For example, the presence of large proper motions in the knots would favor a galactic location. We first searched for 3.6 cm data in the VLA archive and found three epochs (1990, 1995 and 2002) where the source was included in the primary beam of the observations. These data did not result appropriate for a reliable search for proper motions and variability because they have different wavelengths, pointing centers, and phase calibrators. In order to make a reliable, high precision comparison we made new VLA observations in 2006 that match the parameters of the 1995 data. In this paper we present a comparison of these data taken with a time separation of 10.72 years.

## 2. Observations

Our new observations were made with the NRAO<sup>1</sup> Very Large Array, in the B configuration at the wavelength of 3.6 cm, on 2006 September 7 (we will refer to the epoch of these data, taken under VLA project code AR599, as 2006.68). These data have an on-source integration time of 4.9 hours. The 1995 December 16 (epoch 1995.96 taken under VLA project code AW420) data have, as we noted before, the same observational parameters and has an on-source integration time of 3.4 hours. The  $uv$  coverage of both data sets is roughly the same, even when the 2006 data had two antennas missing at the center of two of the arms at the time of the observations.

To obtain two images for reliable comparison we convolved both images to the same angular resolution, resulting in a beam with half power full width of  $0''.86$ . These images were made with the ROBUST parameter of the task IMAGR set to 0.

The absolute amplitude calibration accuracy of the images is uncertain at the  $\sim 10\%$  level. However, due to the good  $uv$  coverage, the relative strength of features in an individual image is measured to higher accuracy. Thus, to allow a direct comparison of the images, we have solved for a relative scale factor which brings the two images into best agreement. Specifically, we combined the images (subtracting the 1995.96 image from the 2006.68 image) in order to get the smallest rms value in the difference image. The final factor for scaling was multiplying the 1995.96 image by 0.93. In the following section we present and discuss these images.

To gain a better understanding of the region as a whole, we searched in the VLA archive for radio continuum observations of lower angular resolution than those discussed here. For the epoch 1984 August 31 we found observations taken at 6 cm under VLA project code AS204 in the D configuration (angular resolution of  $\sim 15''$ ). These observations have been published and discussed by Schwartz et al. (1985) and our conclusions, discussed below, confirm their interpretation. These data were reduced following the standard VLA procedures.

## 3. Results and discussion

We looked for flux density and degree of polarization variations as well as proper motions between the 1995 and 2006 images. In Figure 2 we show the continuum emission from both

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epochs as well as the difference image (2006 - 1995).

### 3.1. Flux Density Variations and Search for Proper Motions

The difference image shows no significant variation in the flux density at a  $5\text{-}\sigma$  level of 0.1 mJy, except for one of the knots, located at  $\alpha(2000) = 06^h 41^m 15.''60$ ,  $\delta(2000) = 09^\circ 26' 45.''774$ , that we identify as the nucleus of the source. In contrast, none of the other knots shows variation above the  $5\text{-}\sigma$  level of 0.1 mJy, that implies upper limits to any variability in the range of 3 to 15 %, according to their flux density.

We also searched for proper motions in the knots, setting typical  $3\text{-}\sigma$  upper limits of 1.6 mas yr<sup>-1</sup>. If the source was located at the distance of NGC 2264, these upper limits would imply  $3\text{-}\sigma$  upper limits of 5.8 km s<sup>-1</sup> for the motion in the plane of the sky. Knots in outflows associated with star formation regions are known to move at velocities in the range of 100 to 500 km s<sup>-1</sup> (Rodríguez et al. 1989; Curiel et al. 2006). In the case of galactic microquasars (Mirabel & Rodríguez 1999), the velocities are much larger, comparable to the speed of light. We conclude that the observed lack of flux density variations and in particular the stringent upper limits to any proper motions argue strongly against a galactic nature for this jet.

As mentioned before, the only knot that is found to be variable in flux density most probably traces the nucleus of this extragalactic jet. This component increased its flux density from  $2.3 \pm 0.1$  to  $3.7 \pm 0.1$  mJy over the period of the observations.

### 3.2. Linear Polarization

On the other hand, the jet presents highly polarized emission, in some knots up to 30% (see Figure 3), including the single knot (most probably a lobe) seen to the west (see Figure 4). One important fact is the absence of detectable polarized emission in the knot presenting variations in flux density (see Figure 3). This supports the idea that this knot is probably the core of a quasar or radio galaxy, that are known to be rapidly variable and to show a small degree of linear polarization, of order 1% (Saikia & Kulkarni 1998). Figure 3 shows that the magnetic field is almost parallel to the jet along most of its extension, except in the final knot where it turns to be almost perpendicular. This polarization behaviour is similar in orientation and percentage to that observed in the jet of the well-known quasar 3C 273 (Conway et al. 1993). Due to the ratio of the fluxes of both sides of the jet, we classified this jet as being one-sided, applying the rules given by Bridle & Perley (1984) and Fanaroff & Riley (1974). This jet seems to be also of type FR II, but the classification implies bright

hot spots in the outer regions, which are not present in this jet.

### 3.3. Large Scale Radio Emission

An image of the VLA archive data is shown in Figure 5. This image is superposed on the STScI Digitized Sky Survey (DSS) red image for the same region. From this overlay, we can see that the Cone nebula is associated with two types of radio emission. The compact double source to its NE is the radio jet discussed here. The more diffuse radio emission associated with the optical emission from the head and the “shoulder” of the Cone is most likely free-free emission from gas photoionized by S Mon, the massive O-type binary located about  $30'$  to the north of the nebula. This diffuse radio emission has a total flux density of  $\sim 10$  mJy. If we assume that it is coming from optically thin free-free emission at an electron temperature of  $10^4$  K, and that the region is located at a distance of 760 pc, an ionizing photon rate of  $5 \times 10^{44} \text{ s}^{-1}$  is required. Furthermore, assuming that the region of diffuse free-free emission subtends an angular diameter of  $1'$  with respect to the angular separation of  $30'$  from S Mon, a solid angle correction factor of  $1.4 \times 10^4$  gives a total ionizing photon rate of  $7 \times 10^{48} \text{ s}^{-1}$  for S Mon. This is consistent with the rate expected from an O7V star, as S Mon is classified (Pagani 1973). We then conclude that these estimates corroborate that the ionization of the Cone is produced by S Mon. Similar conclusions have been reached before by Schwartz et al. (1985) and Schmidt (1974).

There are two relatively bright (about 20 mJy at 6 cm; Girart et al. 2002) sources about  $8'$  to the NW of the Cone Nebula. These sources are known to have non thermal spectra (Schwartz et al. 1985) and most probably are background galaxies. This result suggests that the non thermal jet may be associated with one of the galaxies of a extragalactic background cluster. Unfortunately, given the large obscuration of the region, there are no optical counterparts to any of these sources to test further the possible presence of a cluster.

## 4. Summary

We searched for proper motions and flux variability in the NGC 2264 non-thermal radio jet. We found no proper motions larger (at a  $3\text{-}\sigma$  upper limit) than  $1.6 \text{ mas yr}^{-1}$ . This stringent upper limit appears to rule out a galactic location for the jet, either in the case of a thermal jet emanating from a young star or a relativistic microquasar. We found flux variations only in one knot of the jet, that we identify as the core of the source.

The high degree of linear polarization in the jet and its spatial structure are comparable

with other cases of extragalactic jets. With this evidence, we believe that this object is an extragalactic jet seen in the line of sight toward the NGC 2264 star forming region, even when the *a priori* probability of such coincidence is very low.

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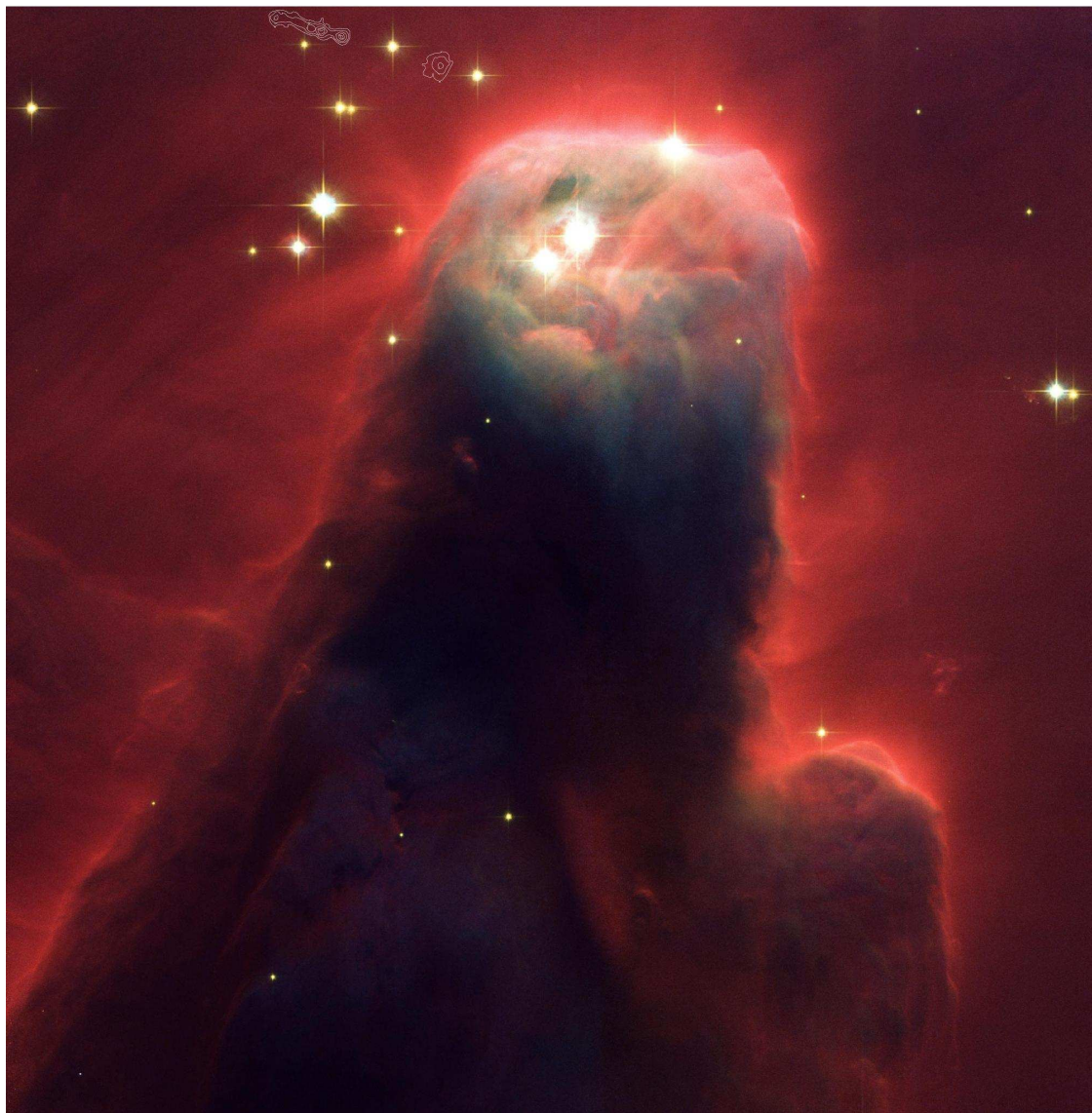


Fig. 1.— This optical image shows in greyscale the Cone Nebula, as observed by the Advanced Camera for Surveys (ACS) aboard the HST. The white contours at the top left come from our radio image of the jet (see Figure 2 for a detailed description of these contours). HST image Credit: NASA, Holland Ford (JHU), the ACS Science Team and ESA.

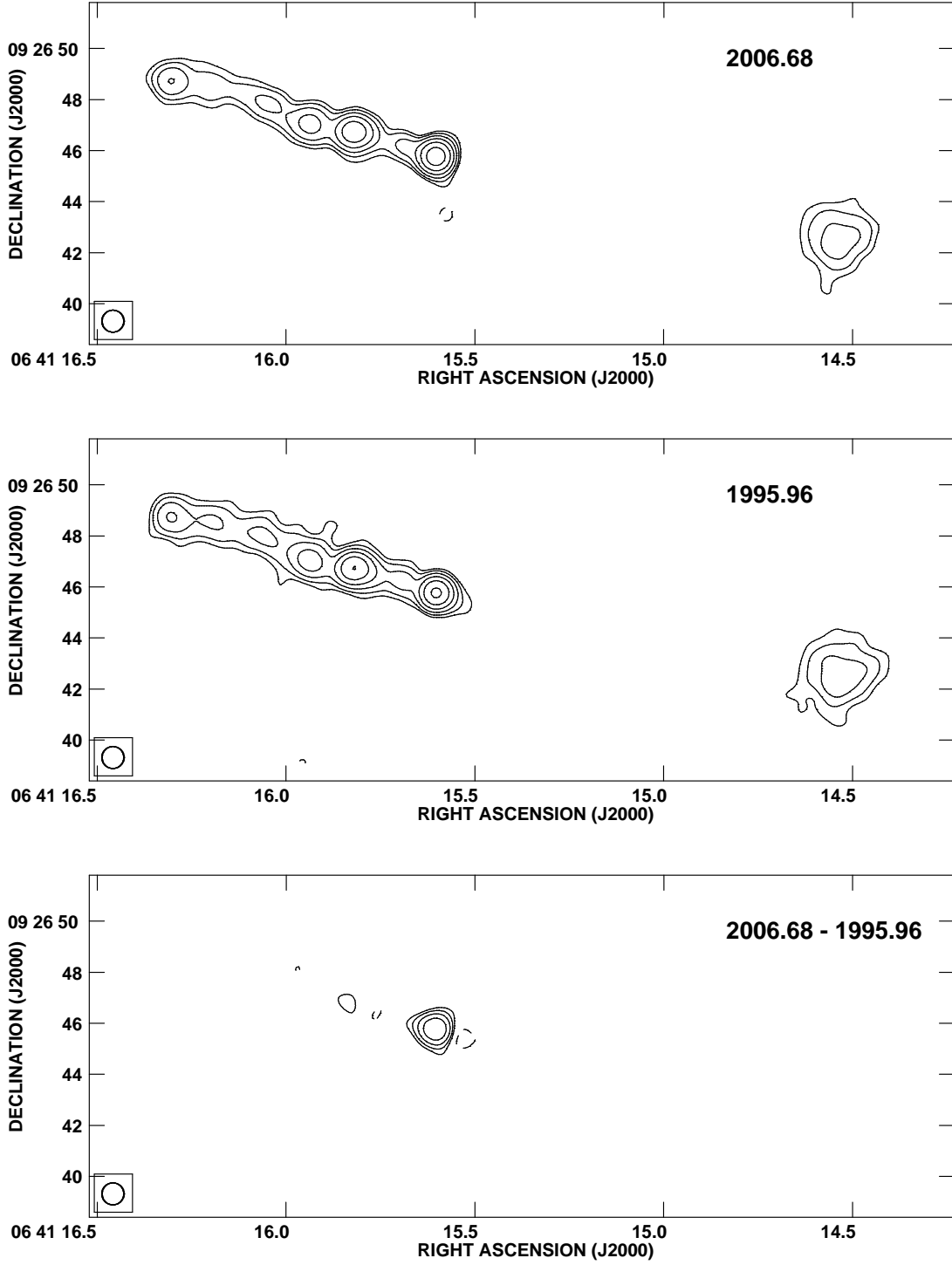


Fig. 2.— 3.6 cm VLA images of the jet, as seen in the 2006 (*top*) and 1995 (*center*) data. The residual image (2006 - 1995) is shown in the bottom panel. The half-power contour of the restoring beam (shown in the bottom left corner) was set to  $0''.86 \times 0''.86$  ;  $PA = 0^\circ$  in order to make a reliable comparison between both epochs. The levels are -4, 4, 8, 16, 32, 64, and 128 times the rms noise (16.3, 13.5, and 21.1  $\mu$ Jy, respectively) of each image.

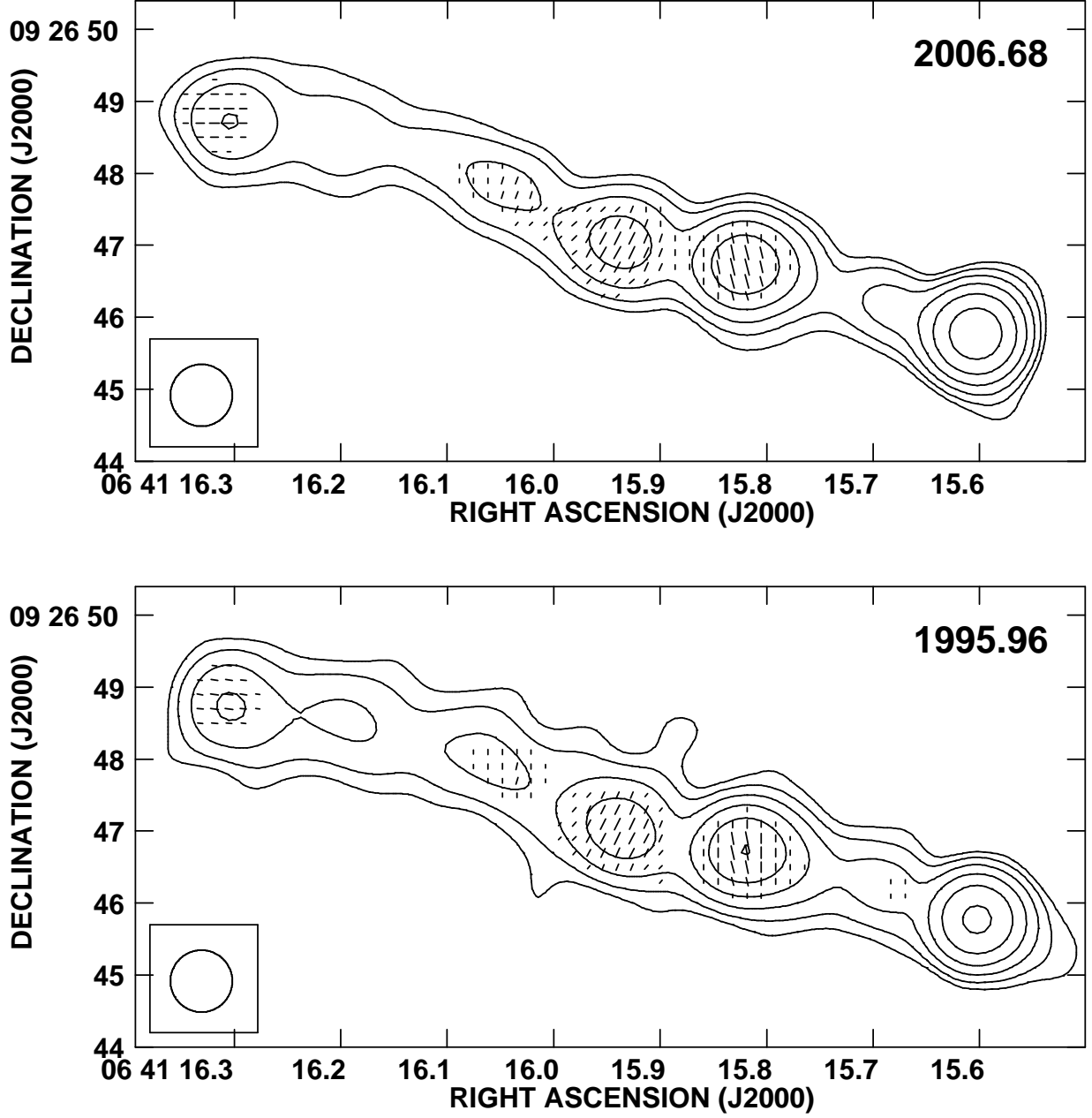


Fig. 3.— VLA images showing the polarization of the east side of the jet for 2006 (*top*) and 1995 (*bottom*). The contours are the same as in Figure 2. The vectors represent the electric vector and its length is proportional to the degree of polarization (0.20 arcsec is 25% linear polarization).

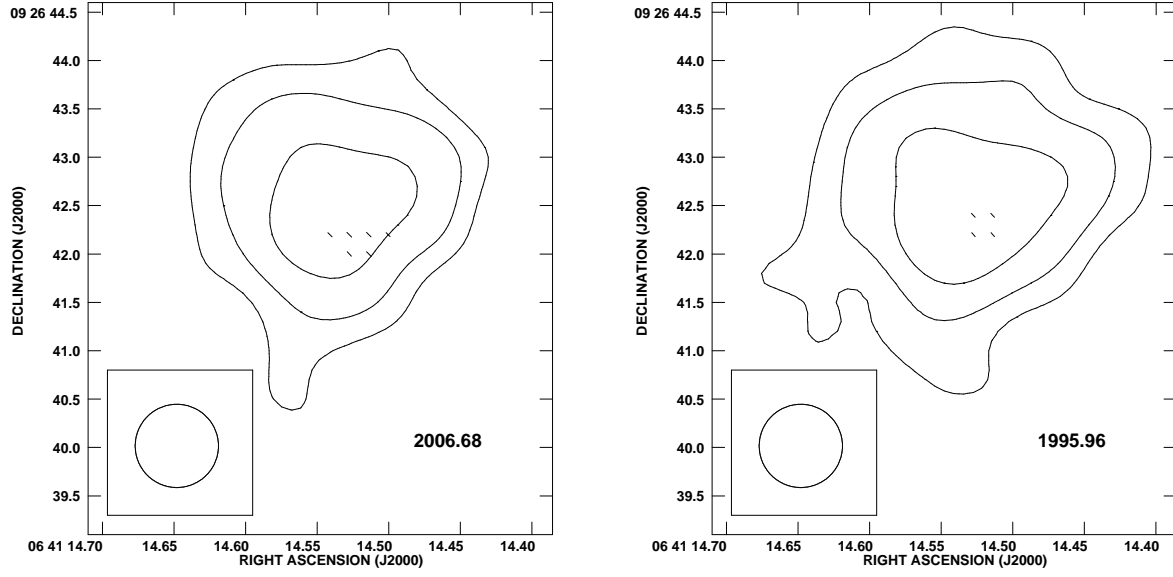


Fig. 4.— VLA images showing the polarization of the west side of the jet for 2006 (*left*) and 1995 (*right*). The parameters are as in Figure 3.

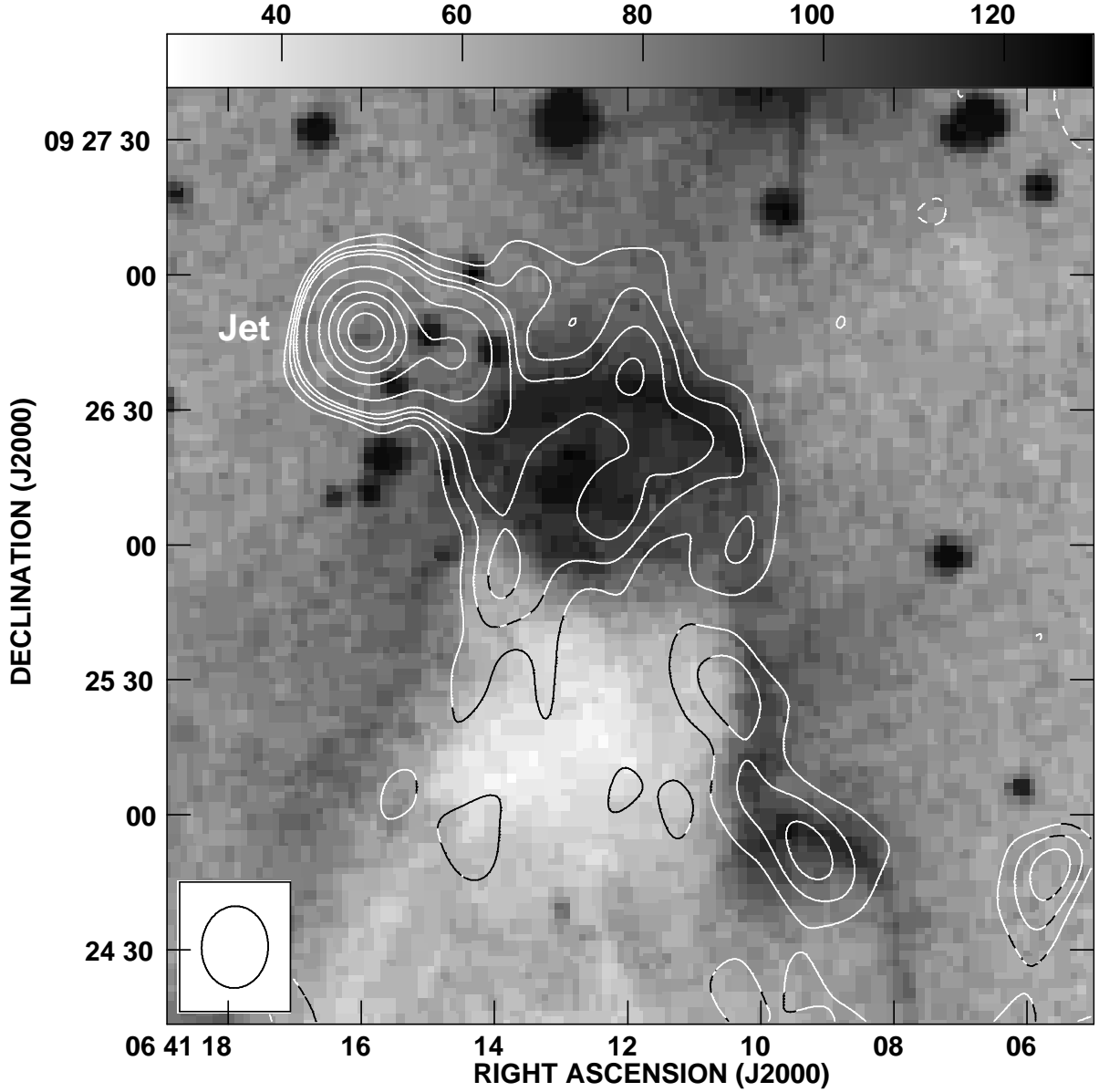


Fig. 5.— This figure shows the Cone nebula in greyscale taken from the red image of the DSS archives. The greyscale bar at the top indicates the intensity of the optical image in arbitrary units. The contours comes from 6 cm VLA-D archive data. The bright, compact double-source to the NE of the head is the non thermal radio jet studied in this paper. The diffuse radio emission associated with the head and “shoulder” of the Cone nebula is most probably free-free emission from gas photoionized by the massive O-type binary S Mon, located about  $30'$  to the north of the nebula. The contours are -4, 4, 6, 8, 10, 20, 40, 60, 80, and 100 times  $112.7 \mu\text{Jy}$ , the rms noise of the radio image. The half-power contour of the synthesized beam of the radio image ( $18''.5 \times 15''.0$ ;  $PA = 0^\circ$ ) is shown in the bottom left corner.